**HWCPP: a C++ library for**

**close-to-the-hardware**

**programming**



**Manual**

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# Summary

HwCpp (Hardware-C++) is a C++ close-to-the-hardware library for writing micro-controller applications. It uses modern C++ features (C++17, concepts TS) to enable efficient code re-use. It relies heavily on unicorns.

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# Introduction

https://xkcd.com/license.html

====================== this whole document is work-in-progress ========================

HwCpp (HardWare library for C++) is a library for efficient and re-usable programming of (small) micro-controllers. It contains abstractions and implementations of for instance GPIO pins, timing (including a cooperative multitasking scheduler), and interfaces to external hardware like SPI and I2C busses, IO extenders, A/D converters, and LCDs. The library is provided under the Boost license, which basically means that you can do everything you want with this software, except that when you re-distribute the source, it must be under that same license.

The library aims to enable target-agnostic programming, and at the same time to be as efficient as C code written for a specific situation. To this end hwcpp makes extensive use of C++ 17 features, compile-time polymorphism, whole-program (link-time) optimization, and some gcc-specific extensions[[1]](#footnote-1), hence a recent gcc compiler is required (gcc 7.2 and later should work, clang will probably work too).

Hwcpp is not a complete development environment, but it can be used with bmptk, which provides a simple make-based build and download environment.

For the situations hwcpp is intended for, some C++ features are often inappropriate. Hence the hwcpp obeys some restrictions:

* No dynamic (heap) memory is used.
* No exceptions are used.
* No RTTI is used.
* No floating-point operations are used directly (but a hwcpp template can be instantiated with a floating point type)

Additionally, to suit my personal taste:

* No global objects that require run-time initialization are used.
* With very few exceptions, the library code compiles without warnings at the highest warning level.

Note that these limitations are *met* by hwcpp; this does not imply that an application that uses hwcpp must also meet these limitations.

Hwcpp is 'work in progress'. The latest version can be found at [github.com/wovo/hwcpp](http://github.com/wovo/hwcpp). If you somehow found and used hwcpp I am very interested to hear your experiences and comments.

The comics in this document are from [www.xkcd.com](http://www.xkcd.com), a definite must-see for everyone involved in computer programming, or otherwise thinks (too) logically.

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The typical blink-a-LED application using HwCpp is:

#include "hwcpp.hpp"

using target = hwcpp::target<>;

using timing = target::waiting;

int main(){

hwcpp::blink< target::led, timing::ms< 200 > >();

}

(This assumes that the target has a default LED, which is the case for the usual suspects like the Arduino Uno, Arduino Due and Blue Pill boards.)

Conventions

Get() and set() operations should be idempotent: a get() operation has no observable side-effects, and in the absence of state-changing effects subsequent get() operations will return the same value as the first. After a set( x ) call, absence of state-changing effects, subsequent set( x ) calls have no observable side-effects.

Classes (in which all functions and variables are static) are used to represent static (compile-time known) objects. Hence :: instead of . is used to access functions and variables within such objects. 🡺 name for such things?

Initialization of static objects is done by calling their init() functions. This is the responsibility of the code that actually uses such objects.

Pins

A pin represents an output, input, input-output or open-collector pin, either on the target chip or on some other location that can be controlled by the target chip.

An output pin can drive an external component, for instance a LED. An output pin can be set to high (power voltage level) by set( true ), or to low (ground level) by set( false ). The initial level of an output pin is target-dependent.

An input pin can read the logic level on the pin, presumably set by external components, for instance a switch and a resistor. The get() function of an output pin will return true when the pin is high (at power voltage level), or false when it is low (ground level).

An input-output pin can be used either as an input pin or as an output pin, as determined by the last direction\_set( d ) call, where d can be either direction::input or direction::output. The output level of an input-output pin directly after a direction\_set(direction::output) call is target-dependent.

An open-collector pin supports both the output and input pin operations (set and get). Electrically, an open-collector pin will pull its output low (connect it to ground) after a set( false ) call, but will leave it floating after a set( true ) call. Such a pin is commonly used with a pull-up resistor.

The pin\_\*\_dummy classes provide pin implementations that do nothing, which can for instance be useful as a placeholders.

The pin\_\*\_value classes provide pin implementations that contain a variable value that reflects the pin value.

Beside the normal set() and direction\_set() functions there are the \*\_direct and \*\_buffered versions. The direct versions take direct effect, the buffered versions can delay their effect until a subsequent flush() or direction flush() call on the pin. Likewise, a get\_buffered() call can return a value that was read earlier, but no earlier than the latest refresh() call on the pin. By default, the normal operations (get(), set(), direction\_set()) are direct (unbuffered) and the flush() and refresh() calls are no-ops. The buffer<> decorator can be used to change the behaviour of those operations to buffered, which is appropriate in situations where multiple (possibly remote) pins are read or updated in an unspecified order. An example of such pins are the pins provided by I/O extender chips, like a PCF8547A.

Pin decorators

The pin\_out<>, pin\_in<>, pin\_in\_out<> and pin\_oc<> decorators change the behaviour to that of a pin conform their name. This serves both as a check that a pin provided by a user can be used as intended, and as a conversion to the intended behaviour.

The buffered<> decorator changes the behaviour of the normal operations to buffered.

The invert<> decorator inverts the value read from or written to a pin.

Arduino Due

The Arduino Due HAL provides static classes for the chip pins according to their Arduino names (a0 .. a11, d0 .. d53, dac0, dac1, cantx, canrx, scl, sda, sca1, sca1, tx, rx, led, sck, miso, mosi, cs0, cs1). Note that some of these names are aliased.

Arduino Uno

<idem>

Blue pill

<idem>

Gcc toolchains

I used the following gcc builds:

* For AVR8 : <http://blog.zakkemble.co.uk/avr-gcc-builds/>
* For Cortex : <http://gnutoolchains.com/arm-eabi/>
* For (windows) native : <https://mingw-w64.org/doku.php/download/mingw-builds>

# Library mechanisms



This section explains some terms and mechanisms used in the library.

Source, sink

Box : get, set, invalidate, flush

Stream : read, write, refresh, flush

Class filters

Public, Library-internal, File-internal

pin\_in\_out\_creator

root class, class filter, class creator, mixin class

how to call the fanout style?

## Files

HwCpp is a is header-only and meant for single-source projects. Normal use is for the user to include hwcpp.hpp and specify the target using a command-line define. The hwcpp.hpp file includes the target-specific header (one of the target-\*.hpp files in the /targets directory), as specified by the define. Alternately, the user could include one of the target-specific header files directly.

A target-specific header includes hwlib-all.hpp, which in turn includes all target-independent files of the library.

The individual HwCpp files are NOT meant to be included directly: they don’t have the multiple-inclusion guards and namespace brackets required for an independent file.

## Dependencies

HwCpp uses C++17 features and the Concepts TS. It has been tested (only) with GCC 7.2.0.

The hwcpp.hpp file requires a command-line defined target. Check this file for the currently supported targets.

Some module tests use Catch2 and assume that the include path is set to find the Catch2 files.

The AVR8 GCC doesn’t provide a (full) standard library. The directory targets/avr8-hacks contains some hacks to make the library work with this toolchain. This directory should be in the include path only when building for AVR8.

The target-specific files assume that the manufacturer’s chip definition files are in the search path. These files are not part of the library, and are not distributed with the standard GCC distributions.

The author uses bmptk, a make-based build-and-download framework for embedded targets, to handle the aspects of embedded application building that are outside the scope of HwCpp. The examples and tests have a chain of Makefile and Makefile.link files that work with bmptk, assuming that it is located ‘next’ to HwCpp.

## Static classes

The main abstraction mechanism used in HwCpp is the static class (and the static class template). A static class is a class (or struct) that has only static elements: static functions, static data, and sub-classes. A static class has no per-instance data and no non-static functions.[[2]](#footnote-2) A static class has no lifetime, hence it can’t cause dangling references. A static class doesn’t have a constructor. Instead all static classes have an init() function that must be called before any data or other functions of the static class is used.

An example of a static class is a GPIO pin. A target board often has a LED that can be controlled by the application. By convention, the pin to which this LED is connected is available as the active-high[[3]](#footnote-3) output pin led. The target itself is available as the class template target, within the namespace hwcpp. The following application first initializes the LED and then enables it.

#include "hwcpp.hpp"

using target = hwcpp::target<>;

int main(){

target::led::init();

target::led::set( 1 );

}

## Interfaces and concepts

A static class implements on or more interfaces. It advertises this by inheriting from the root class, xyz\_rooot for an interface xyz, for each interface it implements. This inserts a tag element[[4]](#footnote-4) into the class, and probably some more items that are mandatory for that interface. For each interface xyz, a concept is\_xyz tests for the marker and the other elements required by the interface. This concept is used to constrain templates that accept only classes that implement a specific interface.

The pin\_out interface is identified by inheriting from the pin\_out\_root. The is\_pin\_out concept tests for the presence of this marker and the other required interface elements: init() and set( bool ).

struct pin\_out\_root {

static constexpr bool is\_pin\_out = true;

};

template< typename T >

concept bool is\_pin\_out = requires( bool v ){

T::is\_pin\_out;

{ T::init() } -> void;

{ T::set( v ) } -> void;

};

An output pin implements the is\_pin\_out interface, hence it inherits from pin\_out\_root. This obliges it to provide (among other things) a set( bool ) function (and of course the obligatory init() function).

struct led : pin\_out\_marker {

static void init(){ . . . }

static void set( bool v ){ . . . }

}

A template that can handle only a pin\_out uses the is\_pin\_out concept to restrict the template parameters it accepts. This is the (simplified) specialization of the invert<> template that handles pin\_out.

template< is\_pin\_out T >

struct invert< T > : T {

static void set( bool v ){

T::set( !v );

}

};

## Adapters

The bulk of the library is coded as wrappers. A wrapper is a function template that takes one or more objects (that each implement an interface), and returns an object that implements an interface. This interface can be the same as one of the argument interfaces or a different one.[[5]](#footnote-5)

The class of the object returned by a wrapper inherits from (and hence implements) one of the libraries interfaces. A wrapper never inherits from one of its arguments: it uses delegation rather than inheritance.

Wrappers that are called X\_from take some arguments, and return an object that implements interface X. Such wrappers are often used to either convert an argument objects into a suitable form, or give a decent compile-time error message if this is not possible.

Run-time duck typing[[6]](#footnote-6) is used by many interpreted ‘scripting’ languages. It implies that a piece of code doesn’t care what type of object it gets passed to work on, as long as that object supports all the operations it wants to do on it during execution. Note *during execution*: if an execution path that is never activated would attempt an operation that is not supported by the object, no one will ever know.

Most hwcpp wrappers use compile-time duck typing: they are templatized on the type of each parameter, hence any type is acceptable, provided that it provides all the operations that the body of the wrapper does on the object. To avoid deep error messages, a wrapper will start with a check that it gets a parameter that is suitable. This is often realized as a conversion of the argument to a more suitable type, using a \*\_from() wrapper.

The blink function shows below is not a wrapper in the normal sense (because it does something instead of returning something), but is shows the way a wrapper accepts an argument. The type of the p argument is a template parameter, hence any (non-const) object is acceptable. The first thing done inside the function is to pass the p to the pin\_out\_from wrapper, which either converts it to a pin\_out (so blink() does not have to bother with for instance setting the direction when it gets passed a pin\_in\_out), or fails with a suitable compile time error message.

template< typename Pin >

void function blink( Pin & p ){

auto pin = pin\_out\_from( p );

. . .

}

## Optimization

Hwcpp objects can be passed as classic OO objects that are used via their virtual functions, but in most cases it preferable to use each object as a distinct type, which causes the compiler to instantiate and optimize the callee for the use of the specific object. This mechanism is essential to get compact and fast code.

The example below shows how a blink function accepts an object as a distinct type. Because all pin objects are unique types, each call to this blink function (with a different pin object) instantiates the template for that object type, which enables the compiler to optimize it for that type, which (with the appropriate compiler settings) eliminates the virtual calls.

template< typename Pin >

void function blink( Pin & p ){

auto pin = pin\_out\_from( p );

. . .

}

// both calls are instantiated and optimized for their pin

blink( target.gpio\_0\_5 );

blink( target.gpio\_0\_6 );

When a function is large and it is called with objects of many different type, a separate instantiation for each type can lead to code bloat. This can be avoided by erasing the type of the passed object down to its interface type, which results in one instantiation of the function being created per interface type. The template function interface() does this, by casting its argument to its interface\_type. This mechanism puts the choice between per-argument instantiation and optimization, or one-function-to-serve-them-all, on the user.

// instantiated once for the interface type of gpio\_0\_5/gpio\_0\_6 (pin\_oc)

// and hence shared by all other pins that are passed as pin\_oc

blink( interface( target.gpio\_0\_5 ));

blink( interface( target.gpio\_0\_6 ));

Functions that are not expected to benefit from being instantiated separately for each argument can be written in the classical way, accepting an object of the interface type by reference. A disadvantage is that such a function accepts only the exact type.

void function foo( pin\_in\_out & pin ){ . . . }

// OK with or without wrapper: gpio\_0\_0 is a pin\_in\_out

foo( target.gpio\_0\_0 );

foo( pin\_in\_out\_from( target.gpio\_0\_0 ));

// wrapper needed: gpio\_0\_5 is a pin\_oc

foo( pin\_in\_out\_from( target.gpio\_0\_5 ));

A disadvantage is that such a function accepts only the exact type.

# I/O pins and ports



The

## pin\_\*

These interfaces define what can be done with a basic IO pin. There are four: pin\_in, pin\_out, pin\_in\_out and pin\_oc. The library has wrapper functions pin\_\*\_from that convert a pin into a different pin, for the cases where that makes sense.

struct pin\_in {

typedef void has\_pin\_in;

typedef pin\_in interface\_type;

virtual void init() = 0;

virtual bool get() = 0;

};

A pin\_in can be used for input only (that is: reading the logical value that is presented to the pin by the outside world). It has (beside the mandatory interface\_type and has\_pin\_in markers) the functions init() and get(). The init() function must be called before get() is called.

struct pin\_out {

typedef void has\_pin\_out;

typedef pin\_out interface\_type;

virtual void init() = 0;

virtual void set( bool value ) = 0;

};

A pin\_out can be used for output only (that is: setting the logical value that the pin presents to the outside world). It has (beside the mandatory interface\_type and has\_pin\_out markers) the functions init() and put(). The init() function must be called before set() is called.

struct pin\_in\_out {

typedef void has\_pin\_in\_out;

typedef pin\_in\_out interface\_type;

virtual void init() = 0;

virtual void direction\_set\_input() = 0;

virtual void direction\_set\_output() = 0;

virtual bool get() = 0;

virtual void set( bool value ) = 0;

};

A pin\_in\_out can be used for both for input and for output. It has (beside the mandatory interface\_type and has\_pin\_in\_out markers) the functions init(), direction\_set\_input(), direction\_set\_output, get() and set(bool). The init() function must be called before any of the other functions is called. Before set() is called direction\_set\_output() must be called. Before get() is called the direction\_set\_input() should probably be called, otherwise the pin is not an input and level that is read will likely depend only on the value that was last passed to set().

struct pin\_oc {

typedef void has\_pin\_oc;

typedef pin\_oc interface\_type;

virtual void init() = 0;

virtual bool get() = 0;

virtual void set( bool value ) = 0;

};

A pin\_oc can be used for both for input and for output, but as output it will only drive the pin low, a set(1) call will make the pin high-impedance (input) rather than driving it high. It has (beside the mandatory interface\_type and has\_pin\_oc markers) the functions init(), get() and set(bool). The init function must be called before any of the other functions is called. The before get() is called set(1) should probably be called, otherwise the level that is read will likely be 0 because the pin is driven low.

## pin\_pullup, pin\_pulldown

struct pin\_pullup {

typedef void has\_pin\_pullup;

virtual void pullup\_enable() = 0;

virtual void pullup\_disable() = 0;

};

struct pin\_pulldown {

typedef void has\_pin\_pulldown;

virtual void pulldown\_enable() = 0;

virtual void pulldown\_disable() = 0;

};

The pin\_pullup and pin\_pulldown secondary interfaces provide operations to enable and disable pullup and pulldown resistors.

These interfaces are generally provided by objects that also provide one of the pin\_in, pin\_out, pin\_in\_out, or pin\_oc interfaces, or one of the corresponding port interfaces.

## pin\_ad, pin\_da

The pin\_ad and pin\_da secondary interfaces define how a pin can provide access to its analog-to-digital and digital-to-analog features.

template< unsigned int n\_bits >

struct pin\_ad {

typedef void has\_pin\_ad;

static constexpr int ad\_bits = n\_bits;

typedef typename uint\_t< n\_bits >::fast ad\_value\_type;

static constexpr ad\_value\_type ad\_maximum =

int\_info< ad\_value\_type >::maximum;

virtual void ad\_init() = 0;

virtual void ad\_start() = 0;

virtual bool ad\_get\_will\_block()= 0;

virtual ad\_value\_type ad\_get() = 0;

virtual ad\_value\_type ad\_start\_get(){ . . . }

};

The pin\_ad interface interface provides the means to use a pin as an analog-to-digital converter. The interface is templated on the number of bits (accuracy) of the converter. The interface provides the has\_pin\_ad type that identifies the interface, three declarations that are derived from the number of bits, and a number of functions.

The function ad\_init() must be called first. After that a conversion can be started by calling ad\_start(). Now ad\_get() can be called, which will busy wait until the conversion is finished and then return the conversion result. The function ad\_get\_will\_block() can be called to check whether ad\_get() will block. The default function ad\_start\_get() simply calls ad\_start() and ad\_get().

template< unsigned int n\_bits >

struct pin\_da {

typedef void has\_pin\_da;

static constexpr int da\_bits = n\_bits;

typedef typename uint\_t< n\_bits >::fast da\_value\_type;

static constexpr da\_value\_type da\_maximum =

int\_info< da\_value\_type >::maximum;

virtual void da\_init() = 0;

virtual void da\_set( da\_value\_type n ) = 0;

};

The pin\_da interface provides the means to use a pin as a digital-to-analog converter. The interface is templated on the number of bits (accuracy) of the converter. The interface provides the has\_pin\_da type that identifies the interface, three declarations that are derived from the number of bits, and the two functions: da\_init() must be called first, and after that da\_set() can be used to set the voltage output by the pin, relative to the maximum value. What happens when a value is set that is larger than the maximum is not defined.

These interface is generally provided by an object that also provide one of the pin\_in, pin\_out, pin\_in\_out, or pin\_oc interfaces.

## pin\_\*\_from

The pin\_\*\_from wrappers convert a pin to a pin\_\*.

template< typename P > auto pin\_in\_from( P && pin ){ . . . }

template< typename P > auto pin\_out\_from( P && pin ){ . . . }

template< typename P > auto pin\_in\_out\_from( P && pin ){ . . . }

template< typename P > auto pin\_oc\_from( P && pin ){ . . . }

The pin\_in\_from() wrapper function will, if possible, create a pin\_in from the object you pass to it. A pin\_in, pin\_in\_out or pin\_oc is acceptable, a pin\_out (obviously) is not. When the object is not acceptable you will get a compilation error.

The pin\_out\_from() wrapper function will, if possible, create a pin\_out from the object you pass to it. A pin\_out, pin\_in\_out or pin\_oc is acceptable, a pin\_in (obviously) is not. When the object is not acceptable you will get a compilation error.

The pin\_in\_out\_from() wrapper function will, if possible, create a pin\_in\_out from the object you pass to it. A pin\_in\_out or pin\_oc is acceptable, a pin\_out or pin\_in (obviously) is not. When the object is not acceptable you will get a compilation error.

The pin\_in\_oc\_from() wrapper function will, if possible, create a pin\_oc from the object you pass to it. A pin\_in\_out or pin\_oc is acceptable, a pin\_out or pin\_in (obviously) is not. When the object is not acceptable you will get a compilation error.

## port\_\*

A port is a list of pins, all of the same type. As for pins, there are input, output, input-output and open-collector ports. The port interfaces are templated on the number of pins in the port. Each port interface has a declaration n\_pins that is the number of pins in the port, and a value\_type that is the type accepted by set() and/or returned by get(). The number of pins that can be part of a port is limited by the number of bits in the largest unsigned integer type that is available.

template< int n >

struct port\_in {

typedef void has\_port\_in;

typedef port\_in interface\_type;

static constexpr int n\_pins = n;

typedef typename uint\_t< n >::fast value\_type;

virtual void init() = 0;

virtual value\_type get() = 0;

};

A port\_in can be used to read from the pins that make up the port. It has (beside the mandatory interface\_type and has\_port\_in markers, and the n\_pins and value\_type declarations) the functions init() and get(). The init() function must be called before get() is called. Get returns a value in which each bit represents the value read from one pin.

template< int n >

struct port\_out {

typedef void has\_port\_out;

typedef port\_out interface\_type;

static constexpr int n\_pins = n;

typedef typename uint\_t< n >::fast value\_type;

virtual void init() = 0;

virtual void set( value\_type x ) = 0;

};

A port\_out can be used to write to the pins that make up the port. It has (beside the mandatory interface\_type and has\_port\_out markers, and the n\_pins and value\_type declarations) the functions init() and set(). The init() function must be called before set() is called. Each bit in the value provided to set() is written to a pin that is part of the port.

template< int n >

struct port\_in\_out {

typedef void has\_port\_in\_out;

typedef port\_in\_out interface\_type;

static constexpr int n\_pins = n;

typedef typename uint\_t< n >::fast value\_type;

virtual void init() = 0;

virtual void direction\_set\_input() = 0;

virtual void direction\_set\_output() = 0;

virtual value\_type get() = 0;

virtual void set( value\_type value ) = 0;

};

A port\_in\_out can be used as port\_out (after direction\_set\_output() has been called), or as port\_in (after direction\_set\_input() has been called. There is no way to switch the direction of individual pins.

template< int n >

struct port\_oc {

typedef void has\_port\_oc;

typedef port\_oc interface\_type;

static constexpr int n\_pins = n;

typedef typename uint\_t< n >::fast value\_type;

virtual void init() = 0;

virtual value\_type get() = 0;

virtual void set( value\_type value ) = 0;

};

A port\_oc supports reading and writing to the set of pins that make up the port. Each pin behaves as an open-collector in: writing a 0 to it makes it low, writing a 1 to it makes it high-impedance (input).

## port\_\*\_from\_pins

|  |
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|  |

TBW

The port\_\*\_from wrapper functions convert a list of pins into a port of the requested type. An individual pin can be retrieved from a port. For use by the port, all pins are converted to the requested type (in, out, in\_out, or oc) using the appropriate pin\_\*\_from wrapper. When a pin is not acceptable to that wrapper a compiler error is generated.

The individual pins of a port can be read (get() function) or written (set() function) in one action. For a port\_in\_out, the direction of all pins can be set, but only collectively.

## port\_\*\_from

TBW

## invert

template< typename P > auto invert( P && p ){ . . . }

The invert wrapper function returns an object that inverts the operation of the object that it gets passed. For digital interfaces (pin\_\* and port\_\*) a 0 will be read or written as a 1, and a 1 as a 0. For pullups and pulldowns all actions on a pullup will result in actions on a pulldown, and vice versa. For proportional interfaces a value x will be read or written as ( max – x ), where max is the maximum value of the interface. When the object is a port, the actions for all pins are inverted.

## mirror

TBW

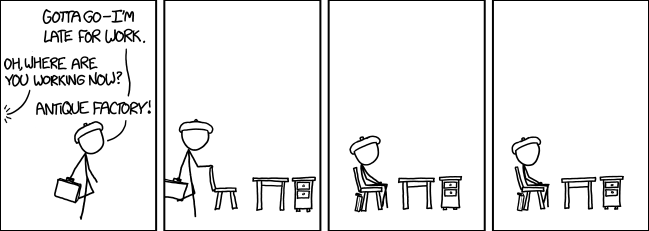
## dummies

Occasionally a dummy pin or port parameter is needed because an interface requires an object, but as far as the user is concerned the operations on the object don’t need to have any effect. For this purpose some dummy objects are provided.

Needs gcc 5 ☹

TBW: tee, both, all, … ?

# Timing



This section explains how the library handles timing (waiting and scheduling).

The library defines three levels of timing service. The basic level is waitd, which offers only (busy) waiting. The next level is clock, which offers (beside waiting) a notion of the current time (since startup), and callbacks for polling. The highest level is thread, which offers (beside waiting, current time, and polling) cooperative multi-threading.

A target provides the highest timing service as target::timing. Lower level timing services are also accessible under their name (target::wait, target::clock, target::thread). An application must use a single timing service.

Waiting

A waiting service the duration templates that create a duration of a fixed number of seconds, milliseconds, etc. A duration has a wait() function that waits (at least) its amount of time. For a waiting service this is busy waiting, for a clock service it can involve servicing callbacks, and for a thread service it can involve servicing callbacks and it can also involve task switching.

Clock

A clock service offers the duration template, but also a function that returns the number of time elapsed since some arbitrary moment. An application can use this to measure time, or to create an overhead-independent delay. It is used by the duration<>::wait() function to service registered callbacks until the requested duration is exceeded.

A callback can be created an registered by calling callback< T >::init(), where T is a class that has a main() function. The callback template in the clock service creates a callback that is called whenever possible, the callback template in a duration creates a callback that is called periodically with the duration as interval.

Thread

To Be Implemented

Relative time is represented by the duration ADT[[7]](#footnote-7), absolute time by the moment ADT, and frequency by the frequency ADT. Time is built into the library because waiting is an essential part of embedded applications, frequency because it is needed to configure a target for a specific clock speed.

Time-related values are stored as long long (signed 64 bit int). [[8]](#footnote-8) Duration and moment are in units of a nanosecond, frequency in units of a mHz. Hence the maximum duration or moment after startup that can be expressed is 292 year.[[9]](#footnote-9)

Each time-related type has an associated set of subtypes that are used to express a compile-time literal value as a unique type. Such subtypes make it possible to force a wrapper that gets such an argument, to be optimized for its specific value. This can be especially important for very small durations, for which a delay() call can be implemented as a few inline instructions instead of a function call.

Timing is provided by a timing service, of which there are three versions: delay, clock, and scheduler. It is up to a target implementation which service(s) it supports and with which accuracy and resolution.

Code, especially library code, should accept a timing service as an argument and be written using only services that provided by the most primitive acceptable timing service. For instance, code that interfaces to an external chip typically must satisfy only some minimum timing requirements; hence it should use only the wait() service as provided by delay.

## Duration ADT

The duration ADT represents an amount of time (a time interval). The ’factory’ functions, member functions and operators related to this type are show in the next table. A duration value is constructed by a call to the ns(), us(), ms() or s() functions. The const\_ns<>(), const\_us<>(),const\_ms<>() and const\_s<>() template functions taken the amount as template argument and create, for each amount, a duration literal: an object of a unique type, derived from duration.

|  |  |  |  |
| --- | --- | --- | --- |
| Duration | | | |
| ’factory’ function | return type | Meaning | |
| ns( x ) | duration | a duration of x nanoseconds | |
| us( x ) | duration | a duration of x microseconds | |
| ms( x ) | duration | a duration of x milliseconds | |
| s( x ) | duration | a duration of x seconds | |
| ns\_literal< x >() | unique subtype of duration | a ’duration’ of x nanoseconds | |
| us\_literal< x >() | unique subtype of duration | a ’duration’ of x microseconds | |
| ms\_literal< x >() | unique subtype of duration | a ’duration’ of x milliseconds | |
| s\_literal< x >() | unique subtype of duration | a ’duration’ of x seconds | |
| member function | return type | meaning | |
| d.ns() | long long | the duration d expressed in nanoseconds | |
| d.us() | long long | the duration d expressed in microseconds | |
| d.ms() | long long | the duration d expressed in milliseconds | |
| d.s() | long long | the duration d expressed in seconds | |
| operator | left argument | right argument | result |
| + | none | duration | duration |
| - | none | duration | duration |
| + | duration | duration | duration |
| - | duration | duration | duration |
| \* | duration | int, long long | duration |
| \* | int, long long | duration | duration |
| / | duration | int, long long | duration |
| / | duration | duration | long long |
| ==, !=, >, <, >=, <= | duration | duration | bool |

## Frequency ADT

The frequency ADT is used to store and manipulate values that represent a frequency. A frequency is stored as a 1/1000s of a Hz. A frequency value is constructed by a call to the mHz(), Hz(), kHz(), MHz() or GHz() functions. The const\_ns<>(), const\_us<>(),const\_ms<>() and const\_s<>() template functions taken the amount as template argument and create, for each amount, a duration literal: an object of a unique type, derived from duration.

|  |  |  |  |
| --- | --- | --- | --- |
| frequency | | | |
| ’factory’ function | return type | meaning | |
| mHz( x ) | frequency | a frequency of x mHz | |
| Hz( x ) | frequency | a frequency of x Hz | |
| kHz( x ) | frequency | a frequency of x kHz | |
| MHz( x ) | frequency | a frequency of x MHz | |
| GHz( x ) | frequency | a frequency of x GHz | |
| mHz\_literal< x >() | unique subtype of frequency | a ’frequency’ of x mHz | |
| Hz\_literal < x >() | unique subtype of frequency | a ’frequency’ of x Hz | |
| kHz\_literal < x >() | unique subtype of frequency | a ’frequency’ of x kHz | |
| MHz\_literal < x >() | unique subtype of frequency | a ’frequency’ of x MHz | |
| GHz\_literal < x >() | unique subtype of frequency | a ’frequency’ of x GHz | |
| member function | return type | meaning | |
| d.mHz() | long long | the frequency d expressed in mHz | |
| d.Hz() | long long | the frequency d expressed in Hz | |
| d.kHz() | long long | the frequency d expressed in kHz | |
| d.MHz() | long long | the frequency d expressed in MHz | |
| d.GHz() | long long | the frequency d expressed in GHz | |
| d.period() | period[[10]](#footnote-10) | the period of the frequency | |
| operator | left argument | right argument | result |
| + | none | frequency | frequency |
| - | none | frequency | frequency |
| + | frequency | frequency | frequency |
| - | frequency | frequency | frequency |
| \* | frequency | int, long long | frequency |
| \* | int, long long | frequency | frequency |
| / | frequency | int, long long | frequency |
| / | frequency | frequency | long long |
| / | long long | period | frequency |
| ==, !=,  >, <, >=, <= | frequency | frequency | bool |

Like for frequencies, there are functions that return a frequency, and function templates that, for each frequency value, return an object of a unique type that is a subtype of frequency.

## Moment ADT

A particular point in time is represented by the moment ADT. It is expressed in nanoseconds stored in a long long (signed 64-bit integer). The zero point will in most cases be the moment the timing service of the target is initialized. The table below shows that a moment can be obtained by calling the now() function provided by a timing service, and that calculations can be done on moments and durations.

|  |  |  |  |
| --- | --- | --- | --- |
| moment | | | |
| function | return type | meaning | |
| now() | moment | returns the current moment in time | |
| operator | left argument | right argument | result |
| + | moment | duration | moment |
| + | duration | moment | moment |
| - | moment | duration | moment |
| - | moment | moment | duration |
| ==, !=,  >, <, >=, <= | moment | moment | bool |

## Delay service

struct delay {

typedef void has\_delay;

void init();

template< typename D > void wait( D d );

};

Delay is the most primitive timing service. The delay struct shows the interface provided by a delay service. The init() function must be called first. Next wait() can be called, which accepts a duration value and (busy) waits for that amount of time. A target can implement waiting for a literal amount of time in a more efficient way, for instance by inserting a few inline instructions. On targets where execution time can’t be easily predicted and that don’t have a timer wait() might not be very accurate, but it will always err towards waiting longer. Delay will probably have the smallest memory footprint of the timing services, especially when only literal durations are used.

## Clock service

struct clock : public delay {

typedef void has\_clock;

moment now();

template< typename D > void wait( D d );

};

The interface of the clock timing service inherits from delay, hence it provided the services offered by delay. Additionally it supports a notion of absolute time in the form of a now() function that returns a moment, and a wait() function that also accepts (besides the duration that is accepted by the wait() provided by a duration service) a moment. As for a delay service, init() must be called first.

A clock service is typically implemented by a free-running 32-bit or 64-bit timer. It is expected to have a modest footprint, somewhat larger than delay. When it is implemented by a timer smaller than 64 bits (most targets don’t have a 64 bit timer) it might be required that, in order for the service to work properly, a call to now(), or wait() with a moment or a non-literal duration argument, must be made every so often, to allow the service to check for and properly handle a timer overflow.

## Scheduler service

A scheduling service offers the services provided by clock, and additionally supports cooperative multithreading.

TBW

# Graphics

This section describes how the library handles graphics.

# External chips

This section documents the library components that interface to external chips.

## I2C

## SPI

## D1W

## ADS7843

## DS18x20

## HC595

## HD44780

## MCP23xxx

## PCF8574(A)

## PCF8591

## PCD8544

# Miscellaneous



## default\_baudrate

constexpr int default\_baudrate = …;

This constant is the default baudrate used for downloading and for communication with the host computer. When used from bmptk, it is the BMPTK\_BAUDRATE, otherwise it defaults to 19200.

## HWCPP\_INLINE

#define HWCPP\_INLINE …

The function decorator HWCPP\_INLINE requests the compiler to always inline the decorated function.

## HWCPP\_REQUIRE\_INTERFACE

#define HWCPP\_REQUIRE\_INTERFACE( P, T ) ...

The macro invocation HWCPP\_REQUIRE\_INTERFACE( P, T ) can be placed in a template to assure that the parameter P has a static void type T in it, which by convention indicates that it implements the interface with that name.

## interface

template< typename T >

typename T::interface\_type & HWCPP\_INLINE interface( T & x ) …

template< typename T >

typename T::interface\_type HWCPP\_INLINE interface( const T & x ) …

The interface template function casts an object or value to its interface\_type. It is used to erase the type of a parameter down to its interface type, to avoid instantiating a different callee for each parameter type.

# Naming conventions

## \*\_from

A wrapper function X\_from returns an object that implements the X interface from another (or the same!) type of object. Such a wrapper can be used at the start of a duck-typed wrapper, to check that a parameter is acceptable, and at the same time convert it to the most convenient type.

## has\_\*

Each interface X has a nested void type with the name has\_X to indicate that the interface is provided. This is used by many wrappers to select the appropriate wrapper for the type of object that is passed.

## interface\_type

Each interface has an interface that is defined as the interface type itself. This is used by the interface() function template to erase the type of its parameter down to its interface type.

# Glossary

This section describes the terms that have a specific meaning in the context of the library. The order in which the terms are introduced minimizes the need for forward references.



## Box, get, set

A box is a thing that has get() and/or set() functions. A box behaves somewhat like a variable: calling get() on a box twice without any intervening changes in the ’world’ should return the same value. Likewise, calling set() twice on a box with the same value should have the same effect as calling it once. A box can be an in-box (has get functions), an out-box (has set functions) or both.

When a box is both an in box and an out box, it has direction functions for switching between in mode and out mode.

Examples of boxes are GPIO pins, ADC and DAC pins, sensors and (absolute) actuators.

## Stream, read, write

A stream is a thing that has read() and/or write() functions. Such functions alter the state of the stream that is read from or written to. Like a box, a stream can be an in-stream (read functions), an out-stream (write functions), or both.

Examples of streams are files and communication channels.

## Blocking

An operation on a stream can be blocking: a read() call can have to wait until something is available to be read, a write() call can have to wait until it is possible to write. To facilitate a user who needs to avoid blocking a stream provides the functions read\_would\_block() and write\_would\_block(). These functions return true when a read or write call would have to wait.

## Buffering

An action on a thing (a box or stream) can be postponed to a later moment, when all operations on that thing can be done more efficiently in one go. To facilitate this, streams and boxes have \_direct() and \_buffered versions of their get, set, read and write functions. The direct ones have immediate effect. The effect of a set\_buffered() or write\_buffered() call can be delayed until the next flush() call on the thing. Likewise, the external reality might not affect what is returned by a get\_buffered() or read\_buffered() call until a refresh() call is done on the thing.

When a box can be switched between in and out mode, it has default, direct and buffered versions of the direction\_set function.

<example>

By default, the unadorned calls are direct. The buffered<> template can be used to create a version for which the default to buffered. This is meant to be done only for use within a limited scope.

<example>

For efficiency reasons, the default behavior for operations on higher-level things like graphic or text windows is in most cases buffered. The direct<> template can be used to create a version for which the default is direct.

<example>

## CTO’s

The main building blocks of the library are (templated or complete) static classes. A static class contains only things that are associated with the class (not with an instance): static const data, static functions, and sub-classes and templates (both of which are inherently static). These static classes act like objects that are created at compile time, hence they are called Compile Time Objects or cto’s.

## Groups

A group is a collection of cto’s that all have the same (minimal) properties. A cto can belong to more than one group.

An example of a of a group is pin\_out. An example of a cto from this group is the target::led present on most target boards.

## ::init()

Each cto has an ::init() function that must be called before any of the services of the cto is used. This call is for a cto what the constructor call is for a run-time object. The responsibility for calling init() on a cto is for the entity that uses the cto. If that using unit is itself a cto, the init call will be part of using unit’s init(). A unit should never assume that a cto that is passed to it (as a template parameter) has already been initialized. An init() function can be called multiple times.

## ::value\_types

Box and stream cto’s contain a type value\_type that is the type of data written to or read from the box or stream.

The value\_type of the various pins is bool, the value\_type of ports is the smallest unsigned integer that can hold one bit for each pin in the port.

## Tags

Each group X has a tag, which is a constexpr bool X\_tag = true; This tag signifies that a cto that has this tag implements the semantics of the group.

## Concepts

For each group X, a C++ concept is\_X<> is defined. This concept checks for the presence of the tag, and preferably for the other properties that should be present. Group concepts are used to constrain template parameters, much like types are used to constrain function parameters.

The is\_pin\_out<> concept test whether cto belongs to the pin\_out group.

## Roots

For convenience, all cto’s in a group derive from a common root class. For a group X the root class (which can be a template) is called X\_root. All roots inherit from uninistantiable to prevent instantiations of cto’s (which would be pointless, and hence probably a mistake).

The pin\_out\_root class is the root of all pin\_out cto’s. pin\_out\_root inherits from box\_out\_root<bool>. This is a specialization of box\_out\_root<T>, which is the shared ancestor of all things you can ::set() to a T value.

## Foundations

A cto that implements the semantics of a group is often created from a simpler one. Such a simpler cto that is used to create a cto of group X is called an X\_foundation.

A pin\_in\_out\_foundation requires only init(), set\_direct(), get\_direct(), and direction\_set\_direct() functions.

## Builders

An X\_builder is a template that constructs an X cto from an X\_foundation.

An example is \_box\_creator<>, which creates a full box (with both default, buffered and direct versions of the relevant functions), from a foundation that has either the direct or the buffered functions (but not both, and no default version).

// This creator is used for instance to create a full pin\_in\_out from a pin\_in\_out\_foundation provided by a HAL.

## HALs

A Hardware Abstraction Layer (HAL) is the code that interfaces directly to the hardware of a target. A minimal HAL provides GPIO (an \_pin\_in\_out\_founcation )and a busy delay function. A more complete HAL provides a monotonic timer, a context switch, and support for its peripherals like UART, ADC, DAC, PWM. Builders are used to create a full-function cto from the foundations provided by the target-specific HAL code.

The sam3xa HAL defines an \_pin\_in\_out\_foundation, and uses the \_pin\_in\_out\_builder to provide a full pin\_in\_out cto.

<>

## Filters

A filter is a template that passes only specific features of its argument. Filters are used in the library to adapt a cto to another kind of cto, which requires passing (only) certain functions.

The \_box\_set\_filter passes only the box set functions of its argument.

template< typename T >

struct \_box\_set\_filter {

using \_vt = typename T::value\_type;

static void HWLIB\_INLINE set( \_vt v ){ T::set( v ); }

static void HWLIB\_INLINE set\_direct( \_vt v ){ T::set\_direct( v );}

static void HWLIB\_INLINE set\_buffered( \_vt v ){ T::set\_buffered( v ); }

static void HWLIB\_INLINE flush(){ T::flush(); }

};

The template that adapts a box\_in\_out to a box\_out passes only the set functions, and amends the init function.

template< \_is\_box\_in\_out T >

struct \_box\_out< T > :

\_box\_out\_root< T >,

\_box\_set\_filter< T >

{

static void init(){

T::init();

T::direction\_set( pin\_direction::output );

}

};

## Wrappers

A wrapper is a template that amends (changes, blocks, etc) only certain features of its argument (if present), and passes its other features unchanged. A wrapper is implemented as a basic template that does nothing, and a specialization for the case that its target features are present. This specialization does the actual wrapping.

An example of a wrapper is the \_no\_inline\_init\_wrapper<>, which passes the init() call, but without forcing it to be inline. All other features are passed transparently.

template< typename T >

struct \_no\_inline\_init\_wrapper : T {};

template< \_has\_box\_out\_functions T >

struct \_no\_inline\_init\_wrapper< T > : T {

static void init(){

T::init();

}

};

This wrapper is used as in step in the \_no\_inline\_wrapper<>. This wrapper is used by the templates that (recursively) create a port from a list of pins. In the recursion, the deeper functions are forced to be inline. The overall function however should not be forced to be inline, which is achieved by applying the \_no\_inline\_warapper<> on the end result.

template< typename T >

using \_no\_inline\_wrapper =

\_no\_inline\_init\_wrapper<

\_no\_inline\_out\_wrapper<

\_no\_inline\_in\_wrapper<

\_no\_inline\_direction\_wrapper< T > > > >;

In terms of patterns, a wrapper can be either a decorator (when it changes the semantics of some functions, but doesn’t change the set of functions), or an adapter (when it adds or removes functions).

## Adapters

It is often too restrictive to limit a template parameter to a single group. It is common for a template to accept a cto from a set of groups, which is converted to a cto of the (for the template code) appropriate group before it is used. In such a case a concept can\_X is used, which accepts any cto that can be converted to X by the adapter X<>.

An example of this pattern is the blink template, which accepts a can\_pin\_out, which is converted to a pin\_out by the pin\_out<> adapter.

template< can\_pin\_out pin, . . . >

void blink(){

using led = pin\_out< pin >;

led::init();

. . .

for(;;){

led::set( 1 );

. . .

}

}

## Dummies

A dummy has no purpose except that it implements the interface of the cto for which it is a dummy. Dummies are used as parameter defaults and as recursion endpoints.

The pin in-out dummy is created from a trivial (do-nothing) pin in-out foundation. The other pin dummies are created from the in-out one by adapters.

struct \_pin\_in\_out\_dummy\_foundation :

\_pin\_in\_out\_root

{

static void set\_direct( bool v ){}

static bool get\_direct(){ return 0; }

static void direction\_set\_direct( pin\_direction d ){}

};

using pin\_in\_out\_dummy = \_box\_builder< \_pin\_in\_out\_dummy\_foundation >;

using pin\_in\_dummy = pin\_in< pin\_in\_out\_dummy >;

using pin\_out\_dummy = pin\_in\_out< pin\_in\_out\_dummy >;

using pin\_oc\_dummy = pin\_oc< pin\_in\_out\_dummy >;

## Naming convention

All declarations in the library (except for a few macro’s) are inside the namespace hwcpp. The naming convention for the library is to use lowercase, and separate the words by underscores (snake\_case).

The library file names use lisp-case. All files in the library start with ‘hwcpp‘. Except for include/hwcpp.hpp, which is the file to include in an application, all library files are in subdirectories of the include directory.

When a name consist of multiple words, the preferred order is largest-first. This is the same order the words would appear when the thing were a nested chain of objects (or cto’s). Variations (like \_direct) are suffixes.

Names that are for internal use by the library start with a single underscore. The (very few) macros are prefixed by HWCPP\_ (or \_HWCPP for internal-use-only macros).

Compile-time object = cto

Immutable

imo

Statca

statcla

name for a static class (template)

compile-time object

rock

brick

singleton

stone

blob

cobble, pebble, pellet

fossiel, versteende afdruk, prent snapshot

speciaal gemaakt product, broodje speciaal

ammoniet

halo, print

prefab

passive

thing

object

stone, keitje

protein

organ

membrum

libris

frobject

brick

numb

icecube

icicle

cryo

frozo

frost

cube

frojo

clobjes

=========================================

Fundament, basis, base, root – builder

inlinkling

grub

proto

primus prime - multiplier

# References

# ToDo

* Header number must have space instead of tab
* Index
* Re-visit the introduction
* Example, gentle introduction
* Explain ‘no offset’ timing loop with now()
* Loop<>
* Targets
* Getting started, way of use
* logical\_or( a, b, … ) \_and \_xor on pins or ports
* filter/debounce
* once, clear\_on\_read
* toggle
* most targets don’t support

1. The extensions used are \_\_attribute\_\_((always\_inline)) and \_\_builtin\_constant\_p(). [↑](#footnote-ref-1)
2. Hence it makes no sense to instantiate an object of a static class, and to doing so will cause a compilation error. [↑](#footnote-ref-2)
3. The hwcpp::target<>::led pin is active high, hence set( 1 ) activates the LED, even when the actual hardware LED is wires active-low (which is often the case). [↑](#footnote-ref-3)
4. The tag is a static constexpr bool named xyz\_tag with value 1. [↑](#footnote-ref-4)
5. Hence a wrapper is a generalization of the decorator (returns same interface) and adapter (returns different interface) patterns. Often the same name is used to for a number of wrappers, selected by the interface implemented by the argument object. Hence one of these wrappers can be a decorator, and the others are adapters, but that only confuses their purpose. The essence (in that case) is that they all return an object that implements the same interface. [↑](#footnote-ref-5)
6. Duck typing refers to the phrase ”If it looks like a duck, swims like a duck, and quacks like a duck, then it probably is a duck.” Or something similar. [↑](#footnote-ref-6)
7. Abstract Data Type: something that behaves more or less like an integer. [↑](#footnote-ref-7)
8. I don’t know what a negative frequency is, but you can express one. The reason is that I wanted to save code size by avoiding using both 64-signed and 64-bit unsigned libraries. The cost is one wasted bit. [↑](#footnote-ref-8)
9. This might cause a problem for a system that runs for more than 292 year without a restart. Don’t expect me to be around when this causes a problem. [↑](#footnote-ref-9)
10. The types returned by the frequency literal\_\* function templates have a period() function that returns a period subtype as it would be returned by duration literal\_\* function templates. [↑](#footnote-ref-10)